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Relaminarization on Swept Leading Edges Under High-Lift Conditions

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Detailed experiments were made to gain an improved understanding of relaminarization on swept wings under high-lift conditions. Two swept wings with different airfoil sections and flaps were tested, and measurements were made consisting of surface-pressure distributions and wall shear-stress fluctuations in the leading-edge zone. Measurements were made at a chord Reynolds number of 1.3 × 10^6 with wing-sweep angles of 45 and 60 deg and model incidence varied in the range of 3 to 18 deg in discrete steps. Following the attachment-line transition, the turbulent boundary layer relaminarized under certain conditions due to the acceleration around the wing's leading edge. Broad features of relaminarization and subsequent retransition are discussed based on wall shear-stress-fluctuation data. The present dataset shows that relaminarization is likely if the maximum value of the acceleration parameter K_s (evaluated along the external inviscid streamline) is greater than about 3 × 10^{-6}, in agreement with earlier findings. Much higher maximum values of K_s result in significant reduction of intermittency during relaminarization. After relaminarization, the boundary layer retransitions across a separation bubble. Characteristics of the postrelaminarization separation bubbles are shown to be similar to those of bubbles occurring in more pristine laminar boundary layers.

Nomenclature

C_p	=	surface-pressure coefficient based on freestream conditions
c	=	airfoil chord along tunnel freestream direction
$\bar{e}$	=	rms value of wall shear-stress fluctuation, V
e'	=	wall shear-stress fluctuation, V
K	=	$(\nu/U^2)(\delta U/\delta x)$, 2-D definition
$\bar{K}$	=	$(\nu/W_e^2)(\mathrm{d}U_e/\mathrm{d}s)$
$\bar{K}_{\mathrm{ave}}$	=	$1/s\int_0^s \bar{K}(s)\,\mathrm{d}s$
K_l	=	local lateral acceleration parameter, $(\nu/Q_e^2)(\mathrm{d}U_e/\mathrm{d}s)\sin^2\psi_e$
K_s	=	local streamwise acceleration parameter, $(\nu/Q_e^2)(\mathrm{d}U_e/\mathrm{d}s)\cos^2\psi_e$
Q_e	=	local freestream velocity
Q_∞	=	freestream velocity far upstream
Re_c	=	freestream Reynolds number based on c
s	=	distance measured along airfoil surface normal to the leading edge, with the origin at the leading edge
U	=	local freestream velocity, 2-D flow
U_e	=	component of Q_e normal to the wing's leading edge
W_e	=	spanwise component of Q_e
W_∞	=	spanwise component of Q_∞
x	=	airfoil streamwise coordinate with the origin at the leading edge
x_s	=	coordinate tangential to the external inviscid streamline
z_s	=	coordinate normal to x_s
α	=	wing incidence
γ	=	intermittency function
Λ	=	wing sweep
ν	=	kinematic viscosity

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I. Introduction

THE flow past a swept wing with its high-lift flap system deployed can be quite complex involving three-dimensionality boundary-layer transition by different mechanisms (e.g., attachment-line contamination, crossflow, and Tollmien–Schlichting instabilities), relaminarization, and confluent wakes. It has been suggested [1–3] that attachment-line contamination (ALC) and relaminarization (RL) near the leading edge of swept wings can cause complicated scale effects under high-lift conditions. Improved understanding of this phenomenon is needed to be able to accurately predict the wing's aerodynamic performance (e.g., maximum lift coefficient, $C_{L\max}$) from the wind tunnel to flight Reynolds numbers.

ALC is typically caused by contamination due to large-scale turbulence emanating from the fuselage boundary layer, and early studies on the subject included a criterion for ALC reported by Pfenninger [4] and Cumpsty and Head [5]. The relevant Reynolds number [4–6] characterizing ALC is $\bar{R} = W_\infty\eta/\nu$, where $\eta = (\nu/U')^{0.5}$ represents a characteristic boundary-layer thickness along the attachment line (ATL) and U' is the inviscid velocity gradient normal to the ATL at the edge of the boundary layer. Available results suggest [4–7] that, if $\bar{R} > 250$, the turbulence will be self-sustaining, causing the ATL as well as the flow downstream of it to become turbulent.

There is now sufficient evidence [1–3,7–14] to show that, following ALC on a swept-wing leading edge, the turbulent boundary layer can relaminarize due to the strong acceleration around the leading edge. The acceleration parameter K, widely used to characterize 2-D relaminarizing boundary layers at low speeds, was first proposed for the occurrence of relaminarization on swept